Hot gas in star-forming galaxies with Constellation-X

Dave Strickland: Draft 2.0

I. Starburst-driven superwinds

A significant fraction of all the heavy elements created by stars in galaxies are ejected by some process into the inter-Galactic medium (IGM), with dwarf galaxies losing 80% of their metals and even massive galaxies like our own losing 10% of their metals (Tremonti et. al 2004). Hot metal-enriched superwinds from starburst galaxies are the most promising metal-ejection process to study at present:

(1) They show the clearest kinematic evidence for galaxy-scale outflows in both the local and high redshift universe (e.g. Heckman et al 2000; Adelberger et. al 2003) of any of these classes of outflow.

(2) They have been observed in star-forming galaxies of all masses and environments, (see Figure 1) from dwarf starbursts such as NGC 1705 and NGC 1569, through moderate and high mass disk galaxies such as M82, NGC 253 and NGC 3628, to ultraluminous merging galaxies, as is required to explain the observed galaxy mass-metallicity (M-Z) relationships.

(3) Almost all starburst galaxies show some evidence for outflow (Lehnert & Heckman 1995), and a substantial fraction (25%) of all (massive) star formation occurs in starbursts within the local universe. Starburst activity was more common in the past. The local space-density of starburst-driven winds of a given size and apparent power is approximately an order of magnitude greater than similar large-scale uncollimated winds from AGN.

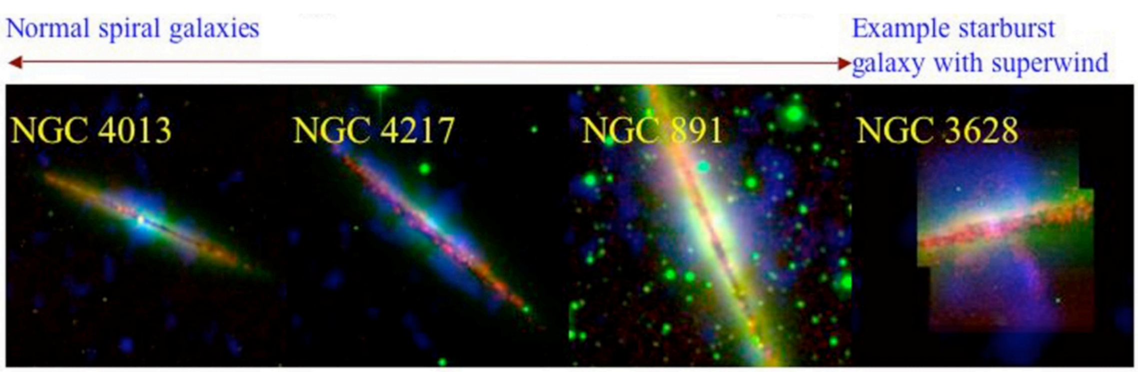


Figure 1: *Hot gas around normal disk galaxies*

Red: H-alpha (WIM), Green: R-band (starlight), Blue: Diffuse soft X-ray (3 million deg gas). The region covered by each image is 20 x 20 kpc. Intensity scale in square-root.

Superwinds are driven by merged core-collapse supernova ejecta and stellar winds, which initially create a 10^8 K metal-enriched plasma within the starburst region. This over-pressured gas expands and breaks out of the disk of the host galaxy, converting thermal energy into kinetic energy in a bi-polar outflow, which can potentially reach a velocity of 3000 km/s. This tenuous wind-fluid sweeps up, entrains, accelerates and possibly shock-heats cooler, denser ambient disk and halo. Theoretical models predict that the entrained, cool gas is accelerated to lower velocities than the hot metal-enriched gas (e.g. Chevalier & Clegg 1985; Strickland & Stevens 2000). These models also predict that the majority of the energy (90%) and metal content in superwinds exists in the hot 10^6 K phases, with the kinetic energy of such gas being several times the thermal energy. *X-ray observations are thus of singular importance in studying this phenomenon, as they provide a probe of the most energetic phases in these outflows, in particular of the metal-enriched phases most likely to escape into the IGM.* Yet all existing observational velocity measurements of superwinds are of entrained cooler material, e.g. warm neutral and ionized gas with 10^3 K with measured outflow velocities in the range 200 to 1000 km/s. Whether this material escapes into the IGM is uncertain, as for the host galaxy (see Heckman et. al 2000).

Despite a wealth of multi-wavelength data on starburst-driven outflows, the fundamental parameters of the absolute element abundances and velocity of the hot gas have not been measured. Observations with *Chandra* and *XMM-Newton* detects thermal X-ray emission from hot gas in superwinds extends out to 5 - 30 kpc from the plane of edge-on starburst galaxies (see Figure 1 and e.g. Strickland et. al 2004a,b), but these observations lack the spectral resolution (ΔE = 100 eV at E = 1 keV) to robustly determine the metal abundance and kinematics of this hot gas. High-resolution X-ray spectroscopy (with $\Delta V \approx 400$ km/s or ΔE = 1 eV at 0.65 keV) is the only method by which these parameters can be measured, and by which the efficiency of winds in ejecting metals can be quantified.

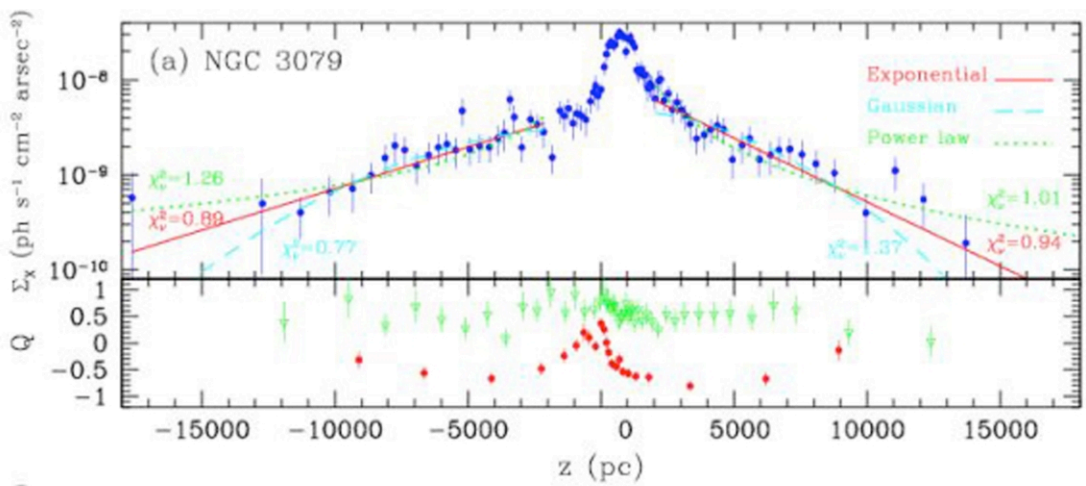


Figure 2: *X-ray surface brightness profiles*

- We observe exponential X-ray surface brightness profiles with Heff ~ 2 – 4 kpc.
- Spectral hardness Q varies only weakly in halo, at z > 2 kpc.
- Inconsistent with conical or radial volume filling wind, would have power law S.
- Consistent with wind hitting and shocking pre-existing exponential halo medium.

II. Hot halos around normal spiral galaxies

The properties of hot gas in the halos around more normal galaxies like our own are even less well understood than starbursts, yet they have the potential to reveal important clues about cosmology, galaxy formation and evolution. By measuring the elemental abundances and composition of the very faint halos of hot gas around normal galaxies we can test theoretical Cosmological models that predict this gas is pristine gas accreting from the IGM (see Benson et. al 2000; Toft et. al 2002; Sommer-Larsen et. al 2003), or see if it is enriched, processed gas ejected from the disk of the galaxy by supernova explosions (galactic “fountains”, e.g. Bregman 1980; Avillez 1999; Norman & Ikeuchi 1989). Current X-ray observatories have only just reached the sensitivities needed to *detect* these extended galactic atmospheres (see Figure 1), but lack the spectral resolution to measure its composition.

Determining the properties of million-degree gas within the disks of star-forming galaxies is also of great importance. On galactic-scales it has long been known that the heavy elements created in stars and released in supernova explosions do not immediately appear (i.e. within a few million years) in the cool, dense gas from which new stars and planets form (Kobulnicky 1998). It has long been suspected that these elements initially enter the hot-X-ray-emitting gas phase, before eventually cooling and condensing into denser clouds (if they are not ejected completely and lost to the IGM in a superwind or galactic fountain). As in the case of superwinds, measurements of the composition and abundances of the diffuse hot gas have been ambiguous with current or previous X-ray telescopes.

High resolution dispersion-less X-ray spectroscopy is the only way of determining: The temperature and ionization state (and hence the energy) of hot 10^6 to 10^8 K gas that has either been recently heated by supernova, or has accreted into the gravitational potential well of massive galaxies such as our own. Current X-ray spectroscopy must assume the gas is in ionization equilibrium, at one or a few well-defined temperatures. This is unlikely to be the truth. The absolute metal abundances (i.e. with respect to Hyrogen) of the hot gas around normal spiral galaxies will be a strong diagnostic of its physical origin: metal-poor gas accreted from the IGM, or element-enriched by supernova activity. High α/Fe ratios are expected if massive stars are the heating source, while lower α/Fe ratios are expected if supernova type Ia can drive the winds (e.g. Wang 2004).

Furthermore, with current instruments, and given the observed spectral features and temperatures of hot gas in normal star-forming galaxies, the spectrally-derived absolute abundances are degenerate with the emission integral (EI H^2V), and so the total hot gas mass and energies are not well determined either. Determine the kinematics (velocities) of this material, and hence its kinetic energy. This is especially important for superwinds, as it is the hot, metal-enriched gas that is thought to have the most energy and is the most likely to escape the host galaxy.

III. Constellation-X: Spatial resolution vs. field of view

Spatial resolution, and the shape of the PSF, does affect the study of diffuse X-ray emission in starburst and normal spiral galaxies. Removal of the majority of point source emission is a real requirement for exploiting high resolution spectroscopy, in that we are trying to measure line strengths and shapes with respect to their continuum. Any additional source of continuum (e.g. unresolved binaries, or contamination from the PSF-wings of bright point source just outside of the field of view) makes the measurement ambiguous. This basically turns into a large uncertainty in absolute element abundances. We would really like to be able to see the thermal continuum from the hot gas itself - it provides useful information on the electron temperature and ionization state information that can not be unambiguously obtained from line diagnostics alone. Some level of spectral-modeling can be done to handle small or moderate contamination, but the less of it the better. The higher the spatial resolution, and the smaller the wings of the PSF, the less of a problem point source contamination of diffuse-region spectra will be.

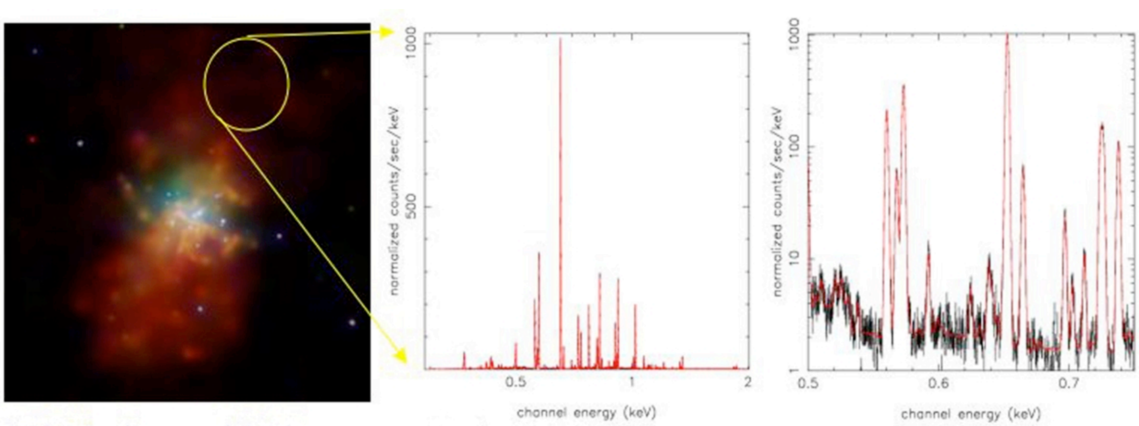
Even in Chandra data, where point sources are detected down to 10^{37} erg/s (10Mpc, 50 ks Chandra), unresolved point source emission is almost certainly present in the disk of edge-on or face-on star-forming galaxies. Effectively complete point source removal (with a decent-sized PSF) is possible for observations of the halo regions of edge-on starbursts and normal spirals, in that we know from Chandra observations where the bright sources are and that the region is effectively a subset of the extra-galactic background (and hence can be modeled reasonably well). These regions are thus good candidates for observation with Constellation-X.

A small or medium FOV would make it more difficult to fully map out the nearest winds, but it is unlikely that that would be done even with a large FOV (assuming that the trade off for higher spatial resolution is a smaller field of view).

The spatial resolution of Constellation-X ceases to be a major factor for more distant objects D~ 200 Mpc z ~ 0.05, where even Chandra can not resolve out the point sources. For such distant objects the separation of diffuse and point source emission components would have to done purely spectrally, as we once did for nearby starbursts with *ASCA*. With prior information from nearby objects it should be possible to avoid the sorts of biases and degeneracies that affected ASCA-based spectra-only studies.

It is hard to choose a specific PSF size that is most advantageous for the study of diffuse thermal X-ray emission in winds and spiral galaxy halos. Furthermore, both the size of the PSF core and its wings are important (even if it is the final 10\% of the energy flux). A small PSF with large shallow wings may be more troublesome that a larger PSF with a steeper drop off at large radii. We found that contamination of spectral regions due to the broad wings in the PSF was a significant issue with regard planning observations of diffuse emission in superwinds with *Astro-E*. Spectrally-dissimilar regions several PSF radii away from chosen target regions always contributed some fraction of the expected/simulated count rate, at levels that could compromise our spectral analysis. Indeed, possible target regions had to be chosen to minimize this effect, at the cost of choosing lower surface brightness (and hence fainter) regions of diffuse emission.

In my opinion, for the study of star-forming objects, good to moderate spatial resolution (5 to 10”) with a small to moderate FOV (1 to 2’. A 1’-diameter FOV is perfectly acceptable) is more important than a larger FOV with lower spatial resolution.



M82 Chandra central 5x5 kpc
red: 0.3-1.1 keV,
green: 1.1-2.8 keV
blue: 2.8-9.0 keV

Simulated 20 ks Con-X northern halo observation, 0.3-2.0 keV.

O VII and O VIII region. Well resolved triplet, high S/N in continuum.

Figure 3 *Courtesy of David Strickland (JHU)*

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IV. Useful numbers

Spectral:

The X-ray spectral energy distribution of the diffuse thermal X-ray emission in superwinds and normal spiral galaxies peaks between E= 0.5 -- 1.1 keV. Telescope performance at energies < 1 keV is important!

Velocity structure (purely informed speculation):

Resolution issues should be able to measure widths to several times better than energy FWHM. 1 eV at 0.65 keV equiv 460 km/s 1 eV at 1.8 keV equiv 170 km/s.

True outflow velocity:

In the soft X-ray could range from that of optically-emitting material (range of 200 – 1000 km/s in various starburst', up to a maximum of 3000 km/s (raw merged supernova ejecta in free expansion). Would only see projected component in edge-on starbursts, 150 km/s in M82 for H alpha = 600 km/s. Should see both velocity offsets from galaxy systemic and potentially even see line splitting within outflowing material (by a few hundred km/s). Should be able to directly probe outflow in face-on galaxies.

Abundances: to be completed

(Requirement is good separation of lines and continuum, measure continuum level well, preferable free of non-related sources of continuum).

Spatial scales:

Angular sizes: 1 arcs equiv 24 , (D 5 , rm Mpc pc. 1 arcm equiv 1.44 , (D5, rm Mpc kpc.

Brightest objects:

- Brightest 8 “typical” (edge-on) starbursts L_{FIR} 10 - 10.5 L lie within 3.6 - 22 Mpc.
- Brightest 8 dwarf starbursts L_{FIR+UV} 10^9 L, all inclinations) lie within 2.2 - 10 Mpc.
- Brightest 8 ULIRGs L FIR 10^{12} L, all inclinations) lie within 84 - 200 Mpc.
- Nearby edge-on normal spirals 200 km/s typically 10 -- 20 Mpc.

Maximum observed vertical extent in X-ray emph emission from center of galaxy:

- Superwinds: depends on host galaxy. For typical starbursts 20 kpc (more typically 10 kpc). For dwarfs 5 kpc (more typically 1 kpc). For ULIRGS 50 kpc.
- Normal spiral hot halos: 5 kpc in NGC 891, 3 kpc for other MW-like spirals.

Mean angular separation between bright X-ray point sources, as detected Chandra:

- Within a starburst region: 1 to 20”
- Normal galaxy disk (seen edge-on): 10 to 30 arcs”
- Halo regions (background X-ray point sources): 30 to 90 arcs”

Spatial scales associated with the diffuse thermal emission:

Spatial structure: In superwinds there is structure on all scales down to *Chandra* resolution/sensitivity limits. Spectral hardness varies from nucleus (central kpc), and from disk to halo (over a vertical height range of 0.5 -- 2 kpc, roughly 10 arcs to 1 arcm). Weaker spectral variations seen in some cases within the superwinds, over several kpc scales. Other spatial scales over which spectral properties may vary in important ways 5 to 30 arcs e.g. across nuclear outflow cones, from wall to center.

Diffuse soft thermal emission as a fraction of FIR luminosity (NB: No IRAS color correction term was applied, so FIR = 1.26 times10^{-11}, (2.58 times 60 + 100 ergps). X-ray luminosity in the 0.3--2.0 keV energy band, thermal emission only.

- Total diffuse (nucleus, disk and halo): L X L FIR = -3.6 pm 0.2.
- Halo region |z| ge 2 kpc): log L X L FIR} = -4.4 pm 0.2

Diffuse emission surface brightness (0.3-1.0 keV energy band, no correction for intrinsic or galactic absorption, units are tons ps pcm 2 arcsec^{-2}:

- Nuclear regions: a few times 10^{-9} to a few times 10^{-7} for the starbursts, a few times 10^{-9} for NGC 891.
- Halo regions: mean value over the entire observed halo is typically from 10^{-9} up to 5 times 10^{-9} for M82 and NGC 253, a few 10^{-9} for NGC 891.